

Mysteries of the large-angle microwave sky

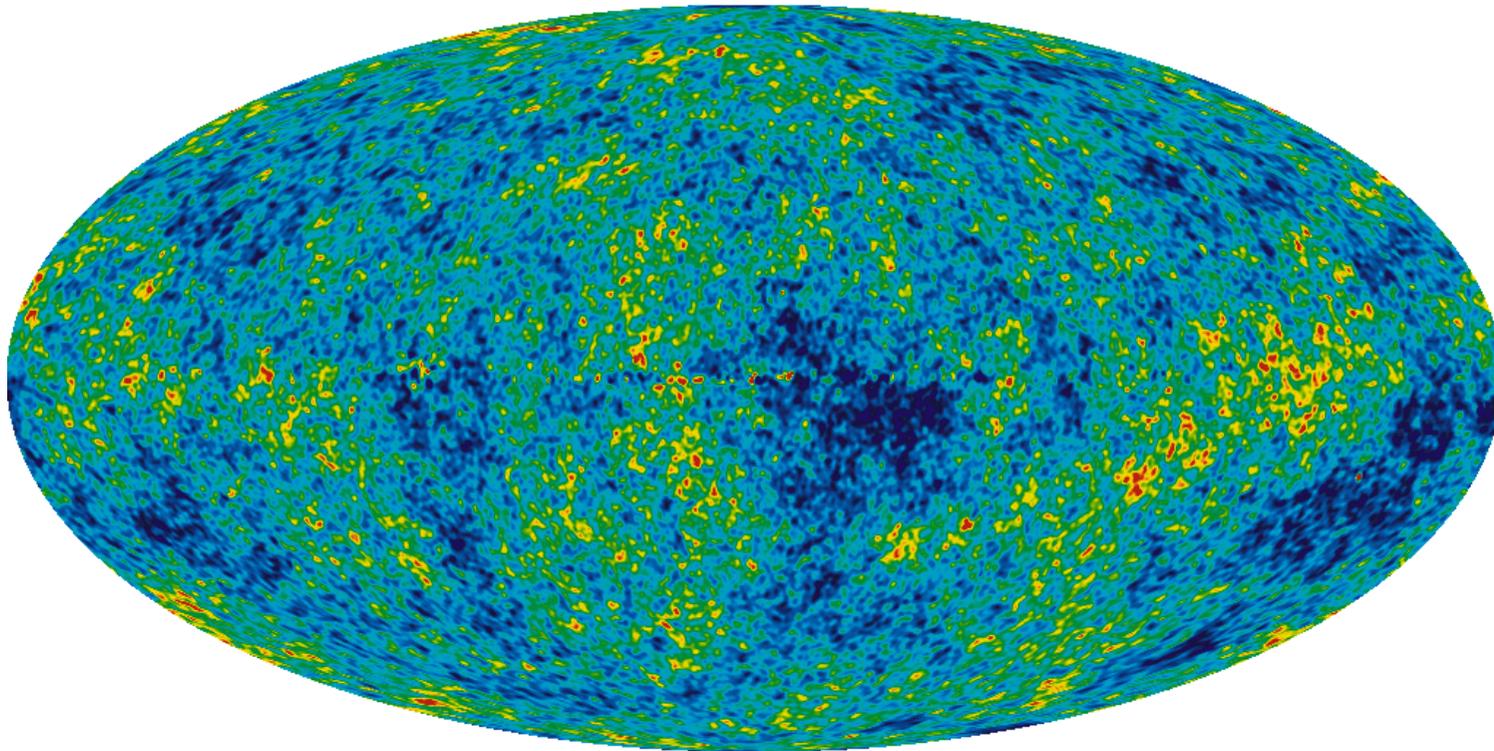
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How does the universe look
at largest observable scales?



ILC map, WMAP collaboration

Outline

This talk is about **correlations** in the CMB,
but the findings may impact measurements of **cross-correlations**

Motivation and overview of concurrent findings

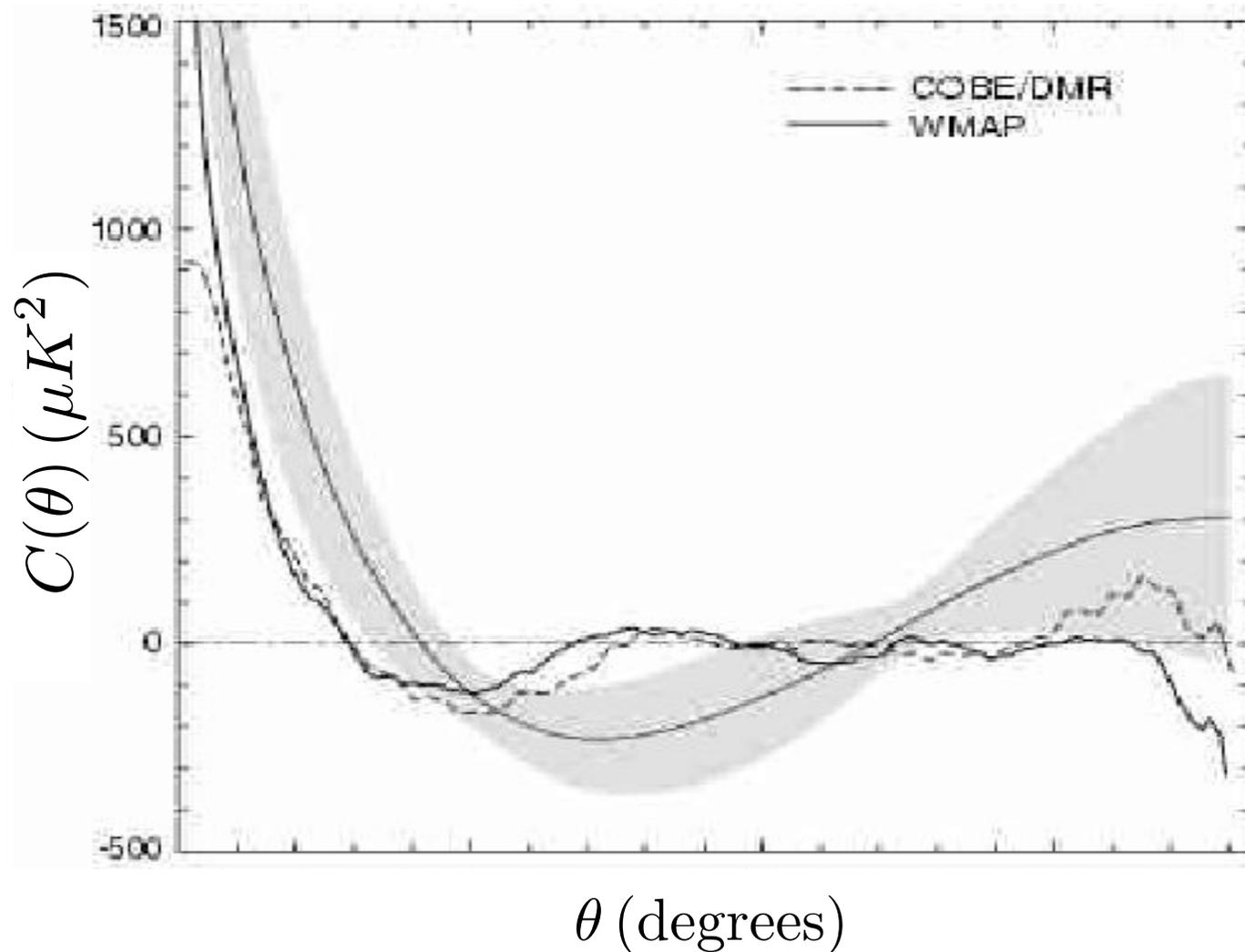
Multipole Vectors

Large-scale alignments

Various explanations

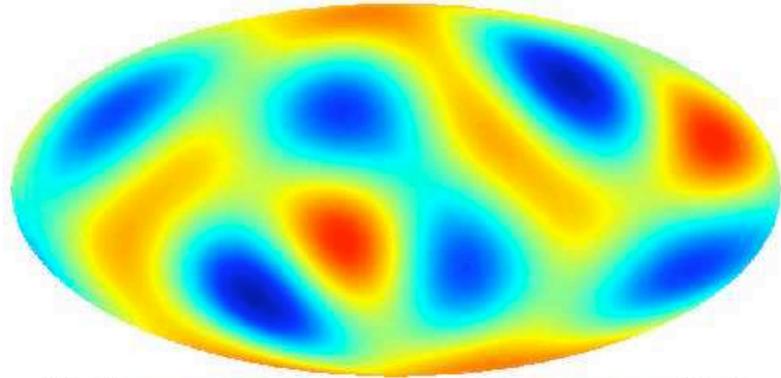
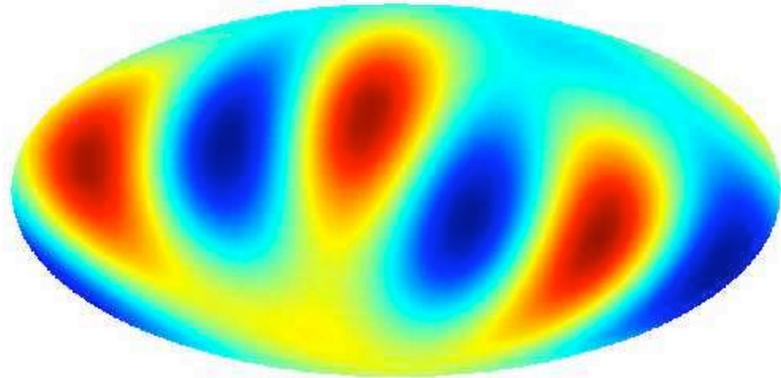
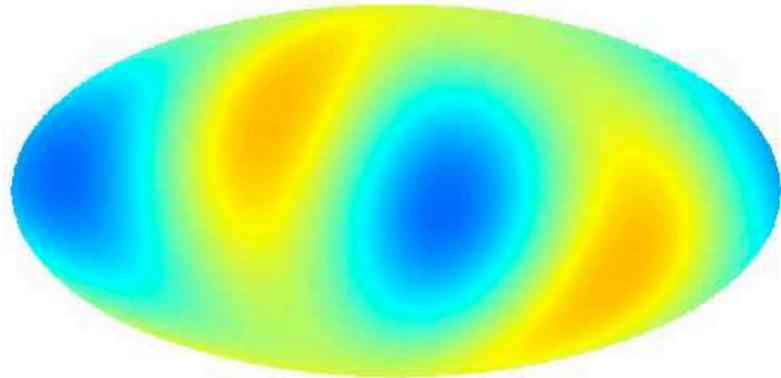
Future prospects and conclusions

Low power on large scales



Spergel et al 2003: **0.2%** of sims have less power at angles >60 deg

$l=2, 3$ are aligned and planar



-34 μ K  34 μ K

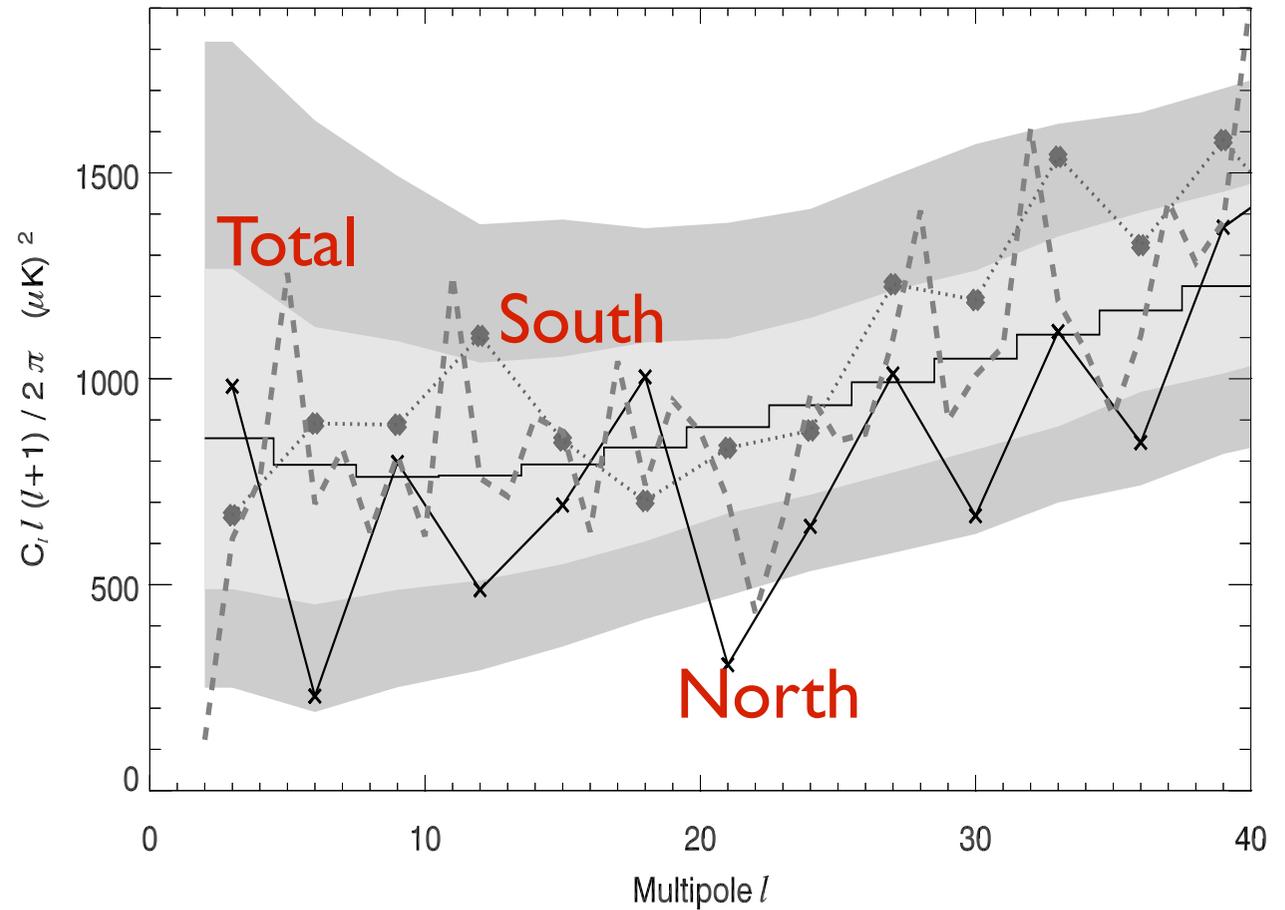
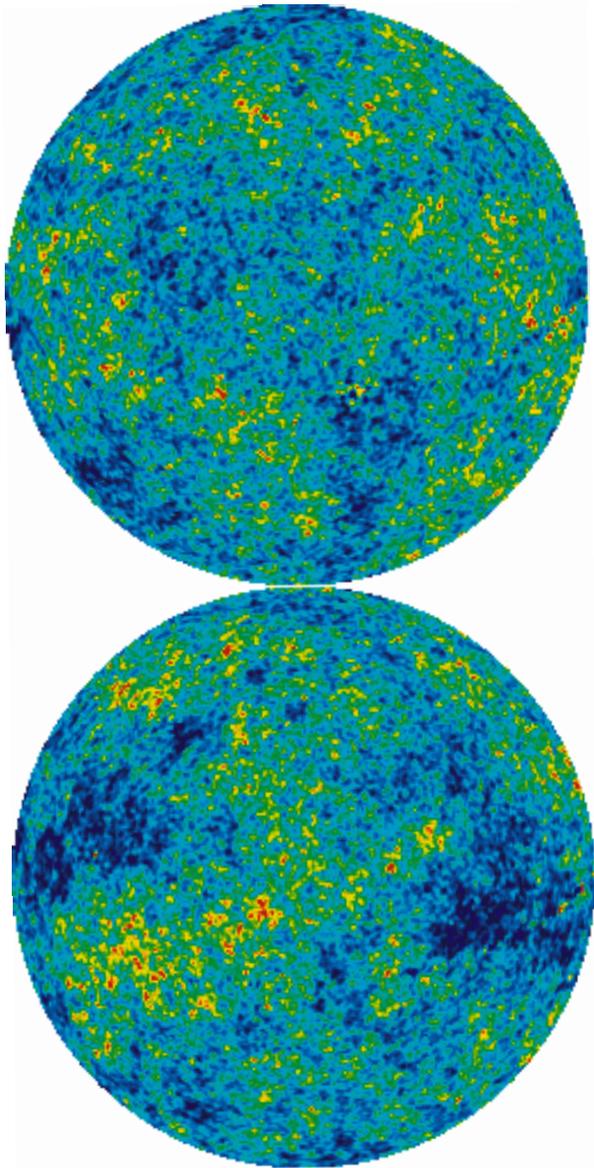
$$\hat{L}_\ell^2 \equiv \frac{\sum_{m=-\ell}^{\ell} m^2 |a_{\ell m}|^2}{\ell^2 \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2}$$

$l=3$ is planar: $P \sim 1/20$

$l=2,3$ are aligned: $P \sim 1/60$

N/S power asymmetry

South (ecliptic) has more power than north



Eriksen et al 2004;
Hansen, Banday and Gorski 2004

Multipole vectors!

Spherical Harmonics:

$$\frac{\delta T}{T}(\theta, \phi) = \sum_{l,m} a_{lm} Y_{lm}(\theta, \phi), \quad C_\ell \equiv \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} |a_{\ell m}|^2$$

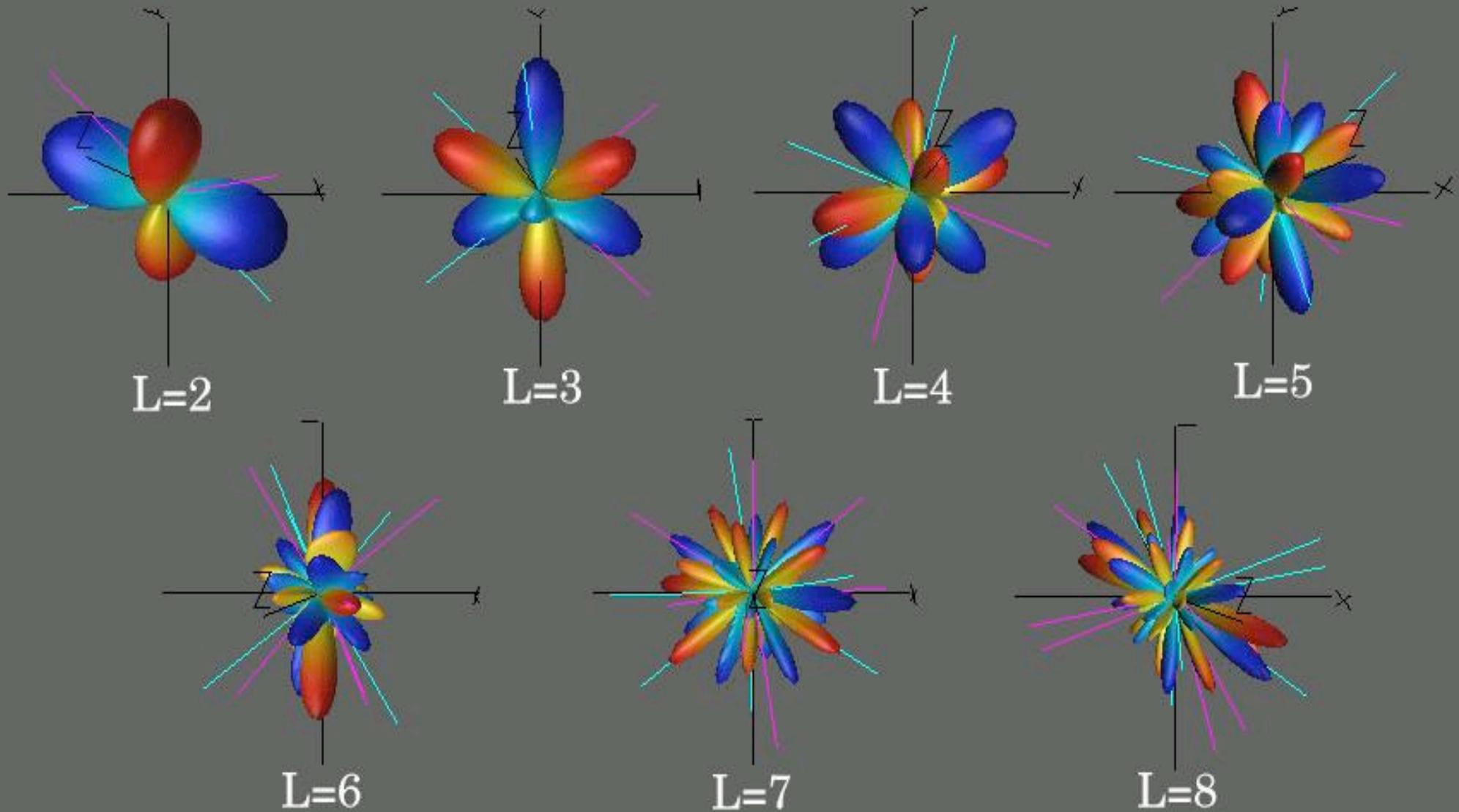
Multipole Vectors:

$$\sum_{m=-\ell}^{\ell} a_{lm} Y_{lm}(\theta, \phi) = A^{(\ell)} \left(\mathbf{v}_1^{(\ell)} \cdot \mathbf{e} \right) \cdots \left(\mathbf{v}_\ell^{(\ell)} \cdot \mathbf{e} \right)$$

$$“a_{i_1 \dots i_\ell}^{(\ell)} \leftrightarrow A^{(\ell)} \left[\mathbf{v}_1^{(\ell)} \otimes \mathbf{v}_2^{(\ell)} \otimes \dots \otimes \mathbf{v}_\ell^{(\ell)} \right]”$$

Lth multipole \Leftrightarrow L (headless) vectors, plus a constant

Multipole vectors of our sky



Maxwell's multipole vectors

Potential of:

Dipole: $\nabla_{\mathbf{v}_1} \frac{1}{r} \left[= -\frac{\mathbf{v}_1 \cdot \mathbf{r}}{r^3} \right]$

Quadrupole: $\nabla_{\mathbf{v}_2} \nabla_{\mathbf{v}_1} \frac{1}{r} \left[= \frac{3(\mathbf{v}_1 \cdot \mathbf{r})(\mathbf{v}_2 \cdot \mathbf{r}) - r^2(\mathbf{v}_1 \cdot \mathbf{v}_2)}{r^5} \right]$

.....

l'th multipole: $\nabla_{\mathbf{v}_\ell} \dots \nabla_{\mathbf{v}_2} \nabla_{\mathbf{v}_1} \frac{1}{r}$

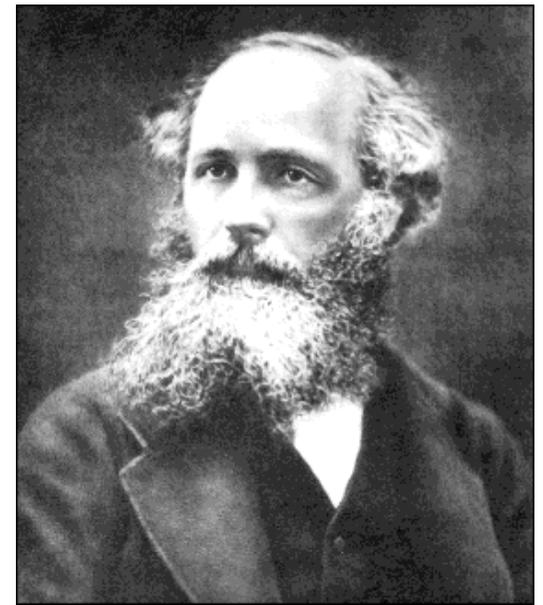
$\mathbf{v}_1 \dots \mathbf{v}_\ell$ are the multipole vectors

Why multipole vectors?

- A **different** representation of the CMB sky than the spherical harmonics, related highly non-linearly
- Ideally suited for looking for **planarity/directionality**
- Many interesting properties, theorems (Katz & Weeks 2004, Weeks 2005, Lachieze-Rey 2004, Dennis 2005...)
- (Reviewed in Copi, Huterer, Schwarz & Starkman astro-ph/0508047)

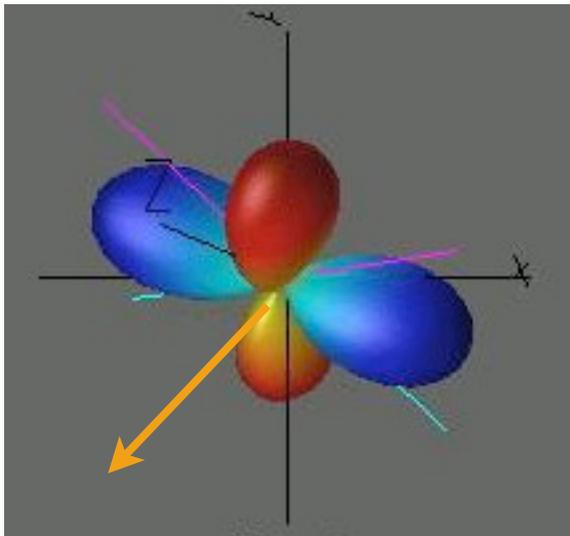
Also:

discussed by J.C. Maxwell in his
“Treatise on Electricity and Magnetism”
in 1892!!

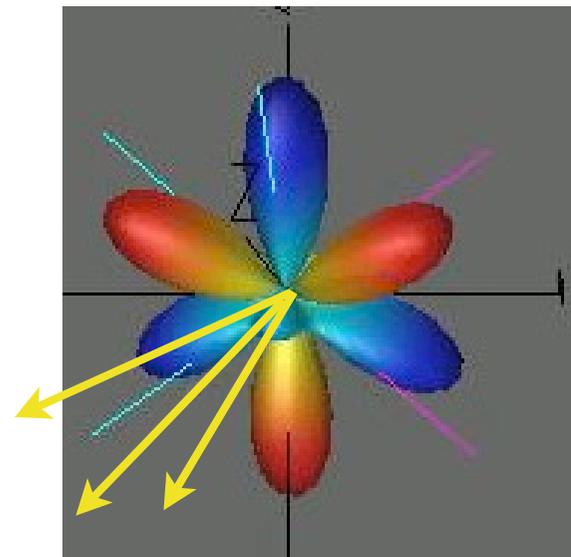


Normals to multipole vectors

$$\mathbf{w}_{ij}^{(\ell)} \equiv \pm \left(\mathbf{v}_i^{(\ell)} \times \mathbf{v}_j^{(\ell)} \right) \quad \text{“oriented areas”}$$

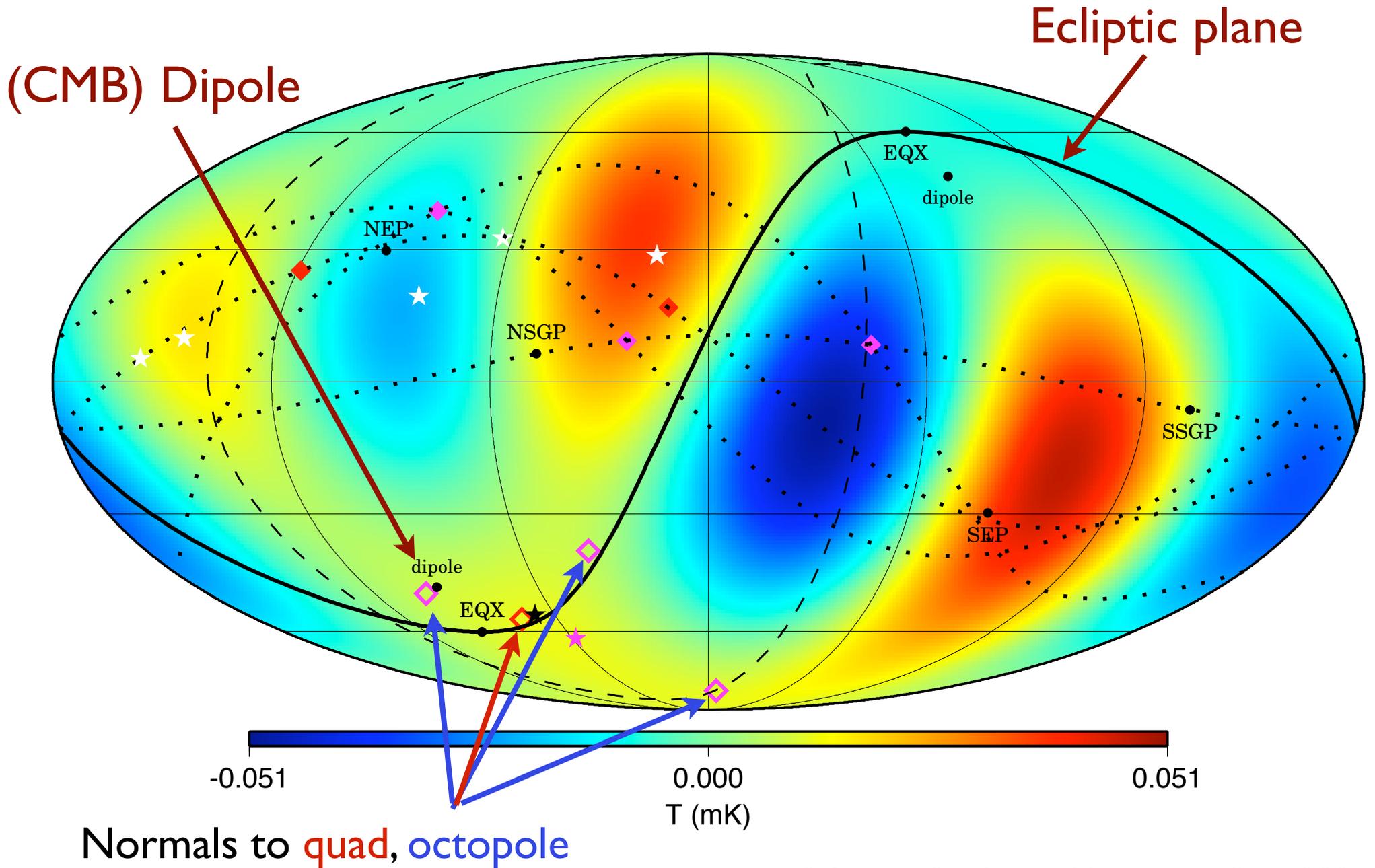


L=2



L=3

L=2+3 alignments

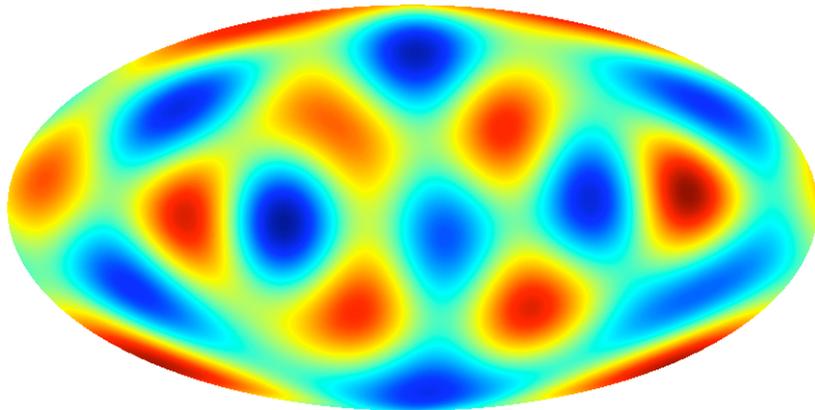


Alignments found at L=2, 3

- The four **area vectors** are **mutually** close (99.0-99.9% CL)
- They lie close to **ecliptic plane** (98%-99% CL)
- They lie close to **equinoxes** and **dipole** (99.8% CL)
- **Ecliptic plane** carefully **separates** weak from strong extrema (93%-99.6% CL)

Axis of evil: $(b, l)=(60, -100)$

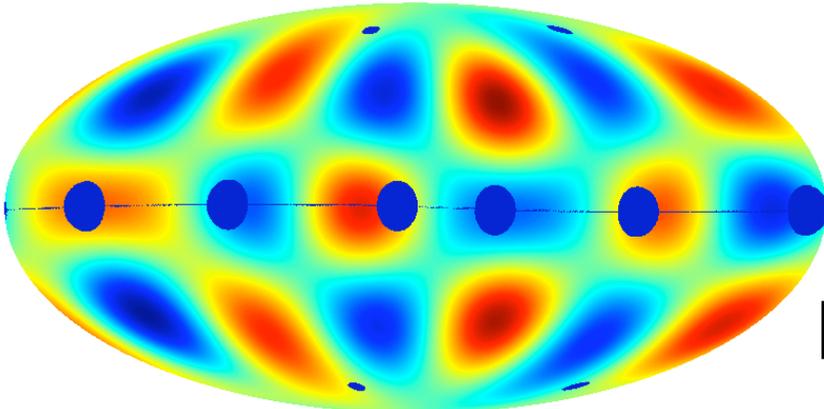
$l=5$ in galactic coordinates



$L=5$, gal frame

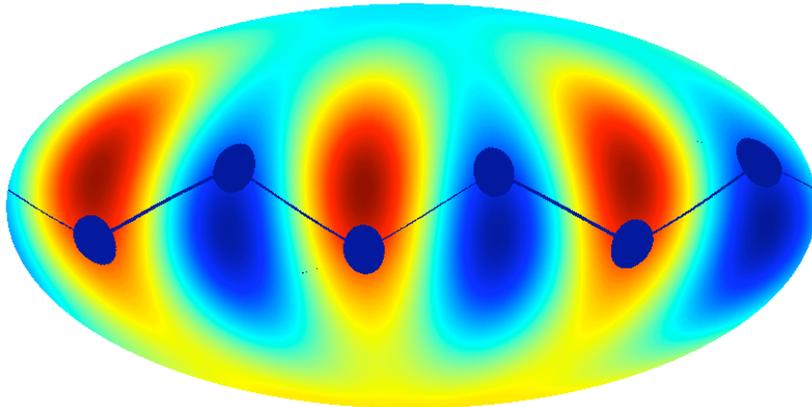
Preferred-axis vectors at $2 \leq L \leq 5$ are unusually close (99.9% CL)

-0.034 $l=5$ in preferred frame 0.034



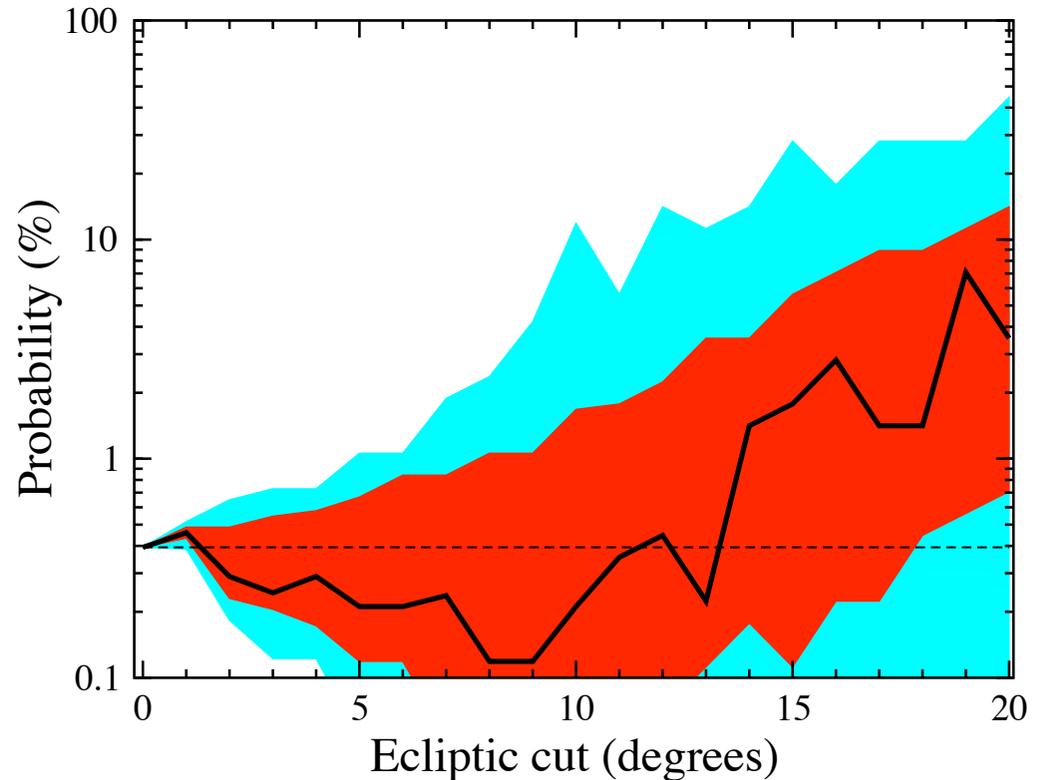
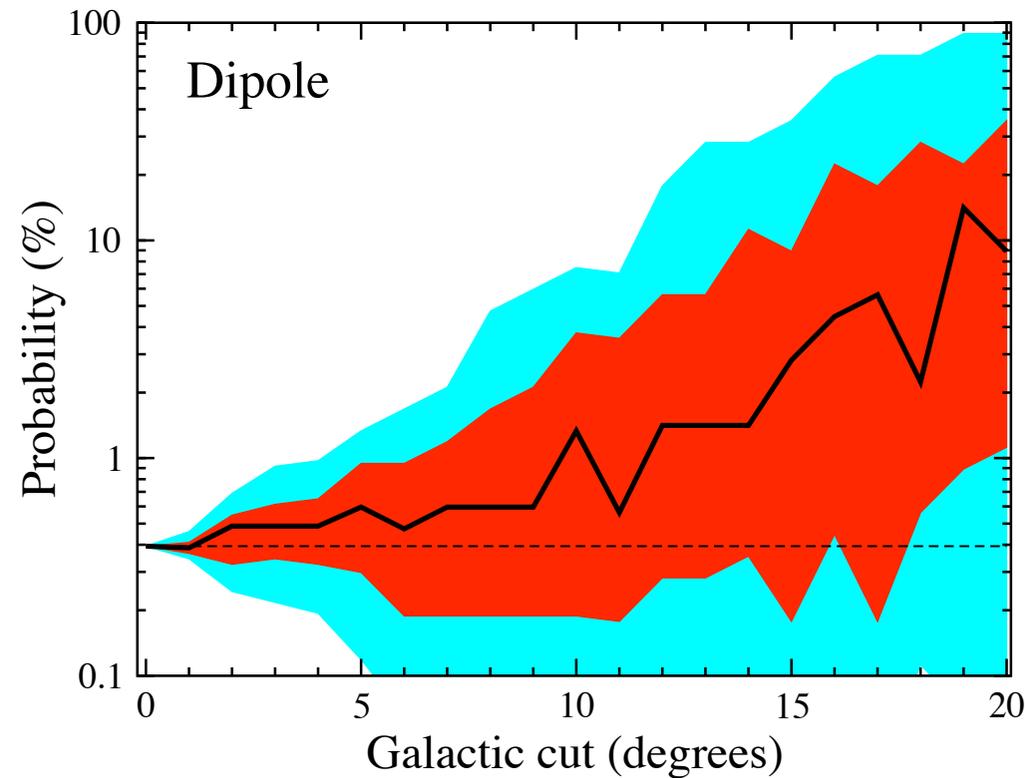
$L=5$, AOE frame

$l=3$ in preferred frame



$L=3$, AOE frame

Systematic checks: sky cut



Errors increase sharply, but results **consistent**
with full-sky result

4 classes of explanations:

- **Astrophysical** (e.g. an object or other source of radiation in the Solar System)
 - BUT: we think we know the Solar System. It would need to be a large source *and* undetected in data cross-checks.
- **Instrumental** (e.g. there is something wrong with WMAP instrument measuring CMB at large scales)
 - BUT: the instruments have been extremely well calibrated and checked. Plus, why would they pick out the Ecliptic plane?
- **Cosmological** (e.g. some property of the universe – inflation or dark energy for example – that we do not understand)
 - This is the most exciting possibility. BUT: why would the new/unknown physics pick out the Ecliptic plane?
- These alignments are a pure **fluke!**
 - BUT: they are <0.1% likely!

Example: non-linear detector

Suppose that the WMAP detectors are slightly (1%)
nonlinear

$$T_{\text{obs}}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}) + \alpha_2 T(\hat{\mathbf{n}})^2 + \alpha_3 T(\hat{\mathbf{n}})^3 + \dots$$

The biggest signal on the sky is the **dipole**

$$T(\hat{\mathbf{n}}) = 3.3mK \cos(\theta)$$

So with $\alpha_2 \sim \alpha_3 \sim 10^{-2}$, dipole anisotropy is modulated into a 10^{-5} quadrupole and octopole with $m = 0$ **in the dipole frame**.

Sadly: **doesn't work** since would have been seen when observing $\sim 1K$ sources (in lab, Jupiter, etc).

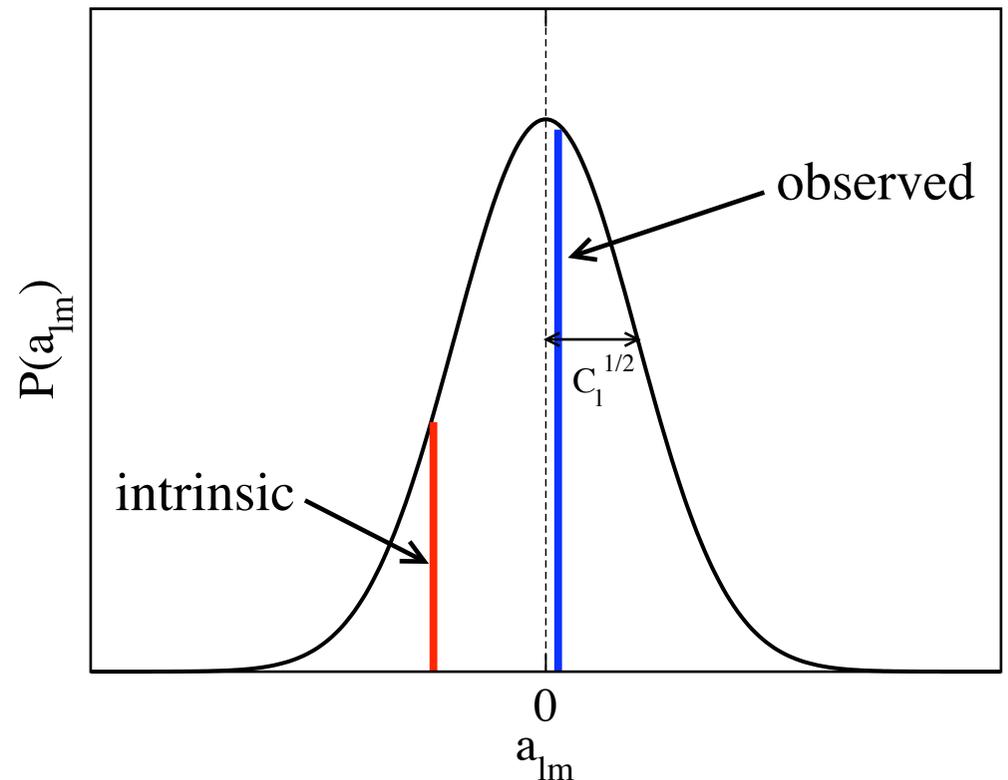
Additive schemes “don’t work”

$$\hat{T}(\hat{\mathbf{n}}) = T_{\text{intr}}(\hat{\mathbf{n}}) + T_{\text{extra}}(\hat{\mathbf{n}})$$

Double (likelihood) penalty:

- Intrinsic sky is **less likely** than observed
- Requires a **chance cancellation**

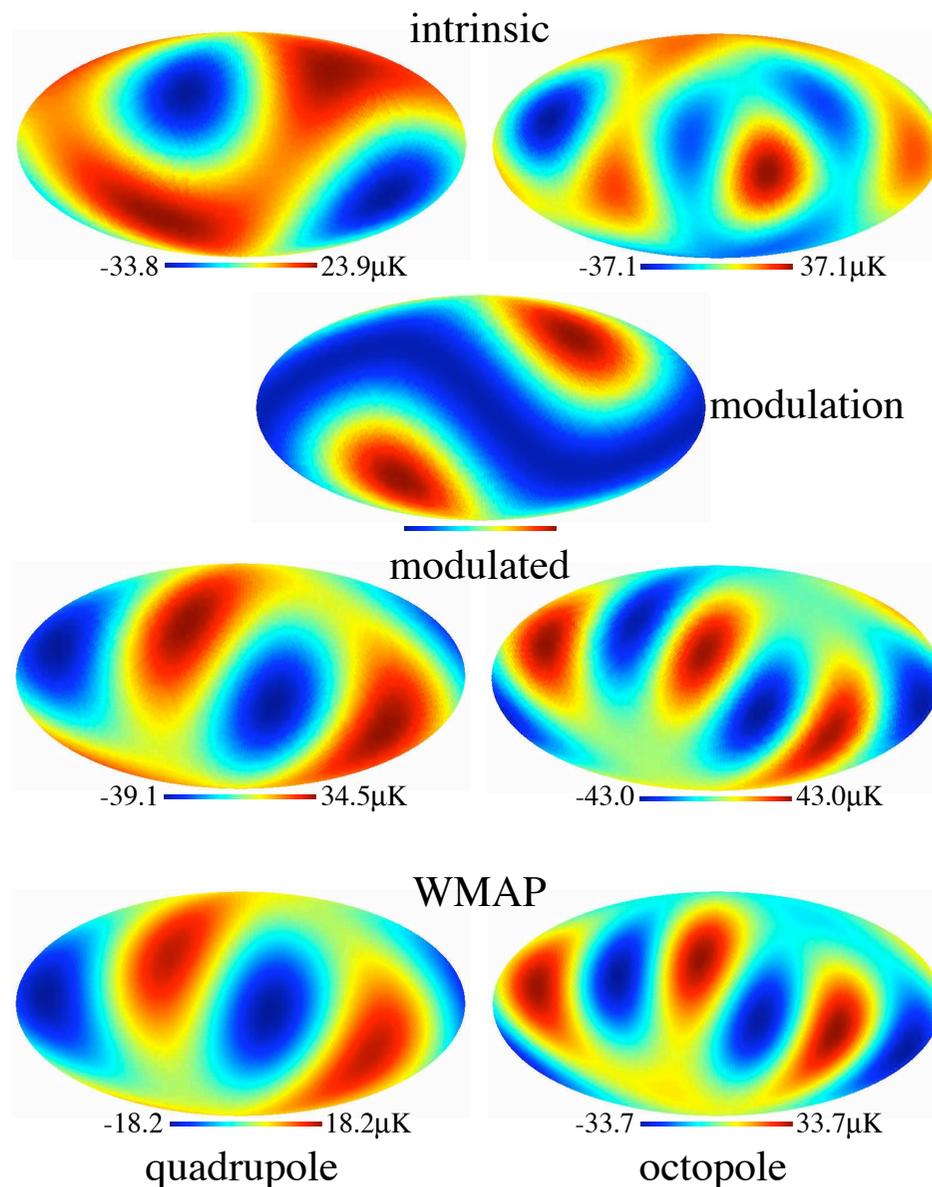
True for all additive schemes:
Solar System contamination,
Bianchi models,
etc



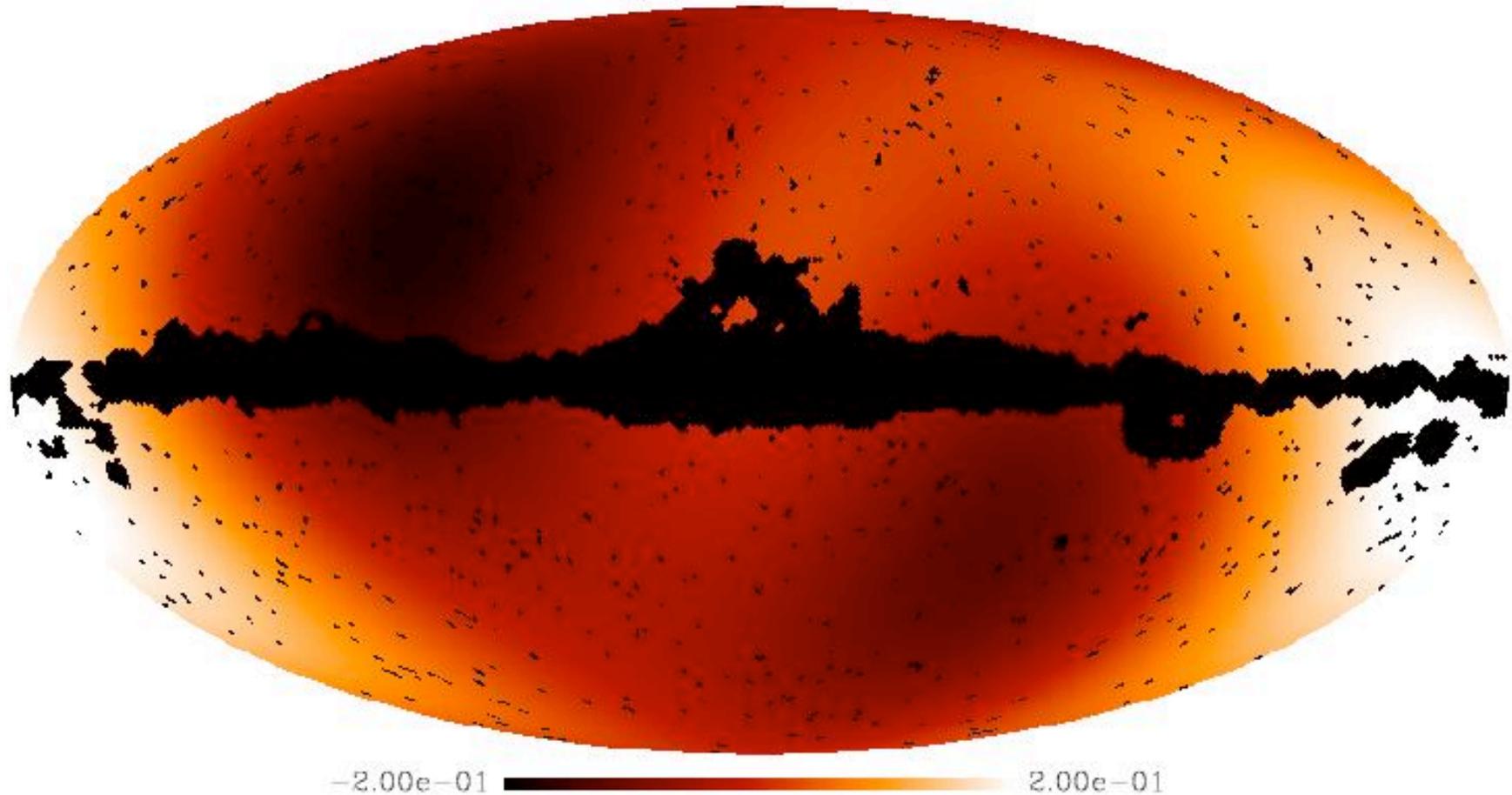
Multiplicative modulation can work

$$\hat{T}(\hat{\mathbf{n}}) = T(\hat{\mathbf{n}}) [1 + w(\hat{\mathbf{n}})]$$

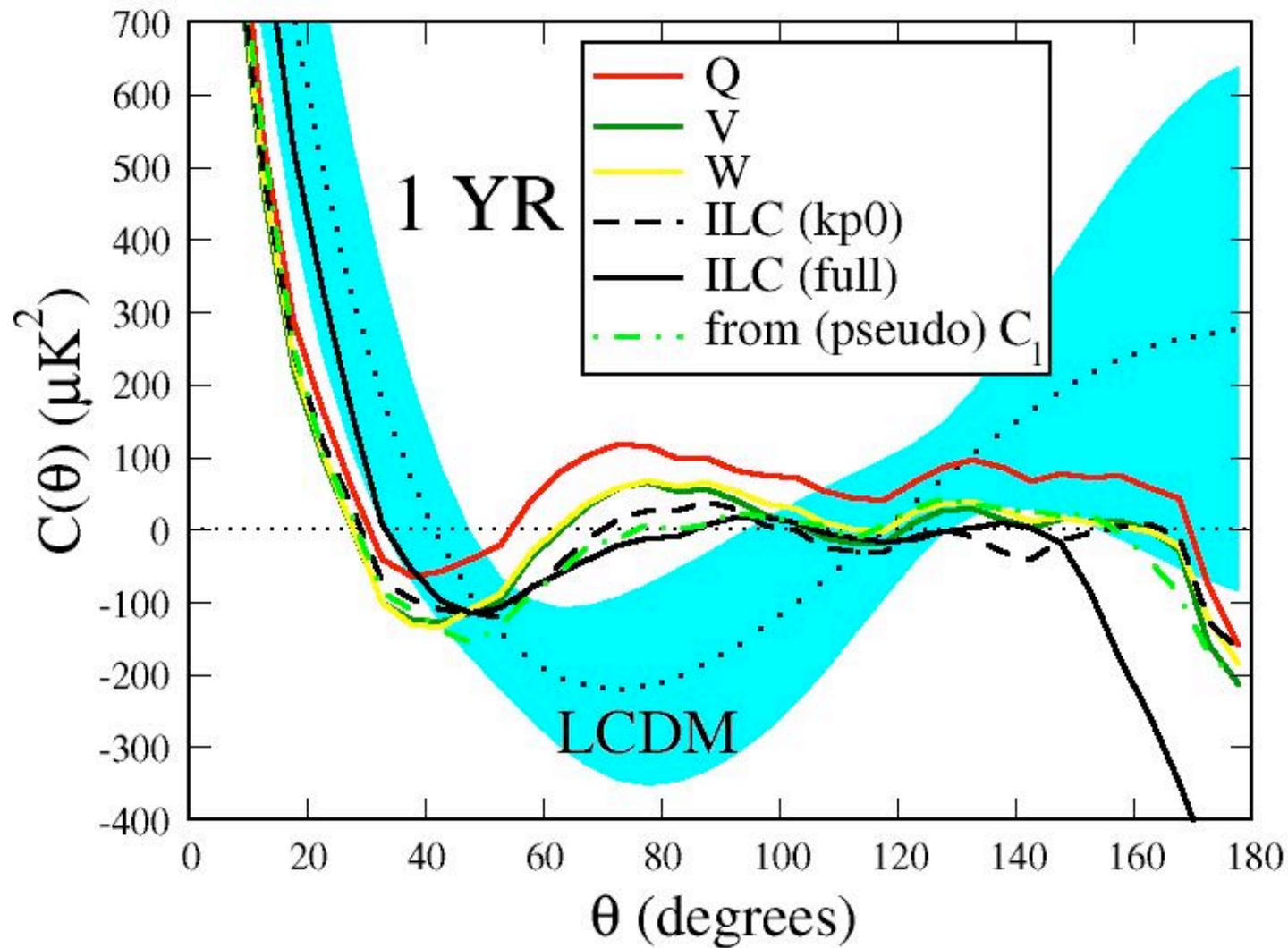
$$w(\hat{\mathbf{n}}) \propto Y_{20}(\hat{\mathbf{n}}) \quad \text{example}$$



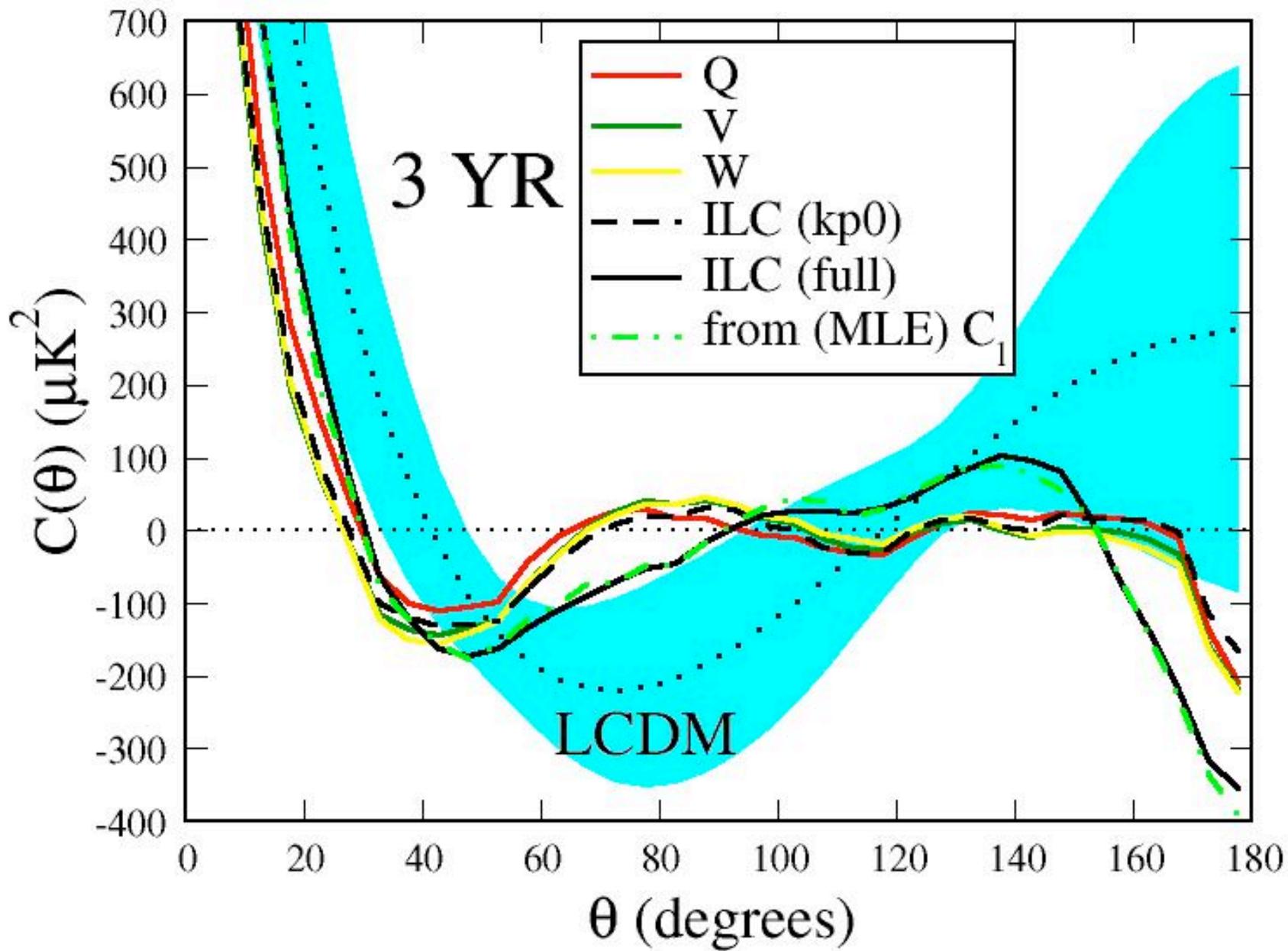
Best-fit $L=1,2$ multiplicative modulation from WMAP 123

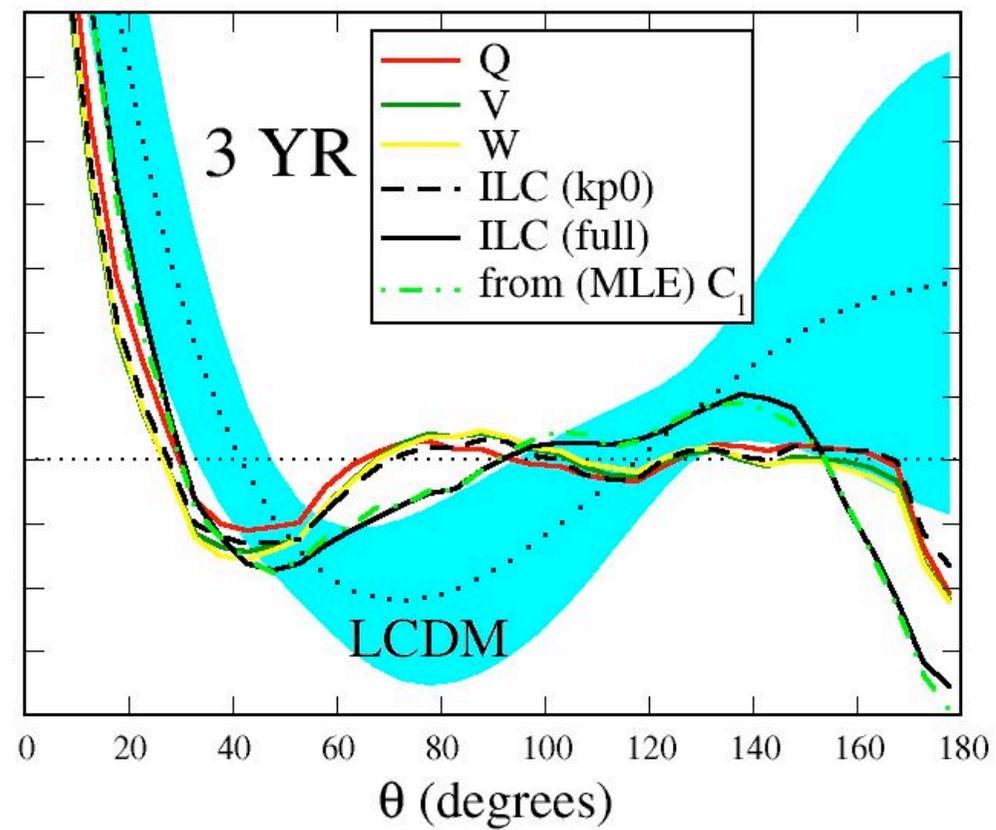
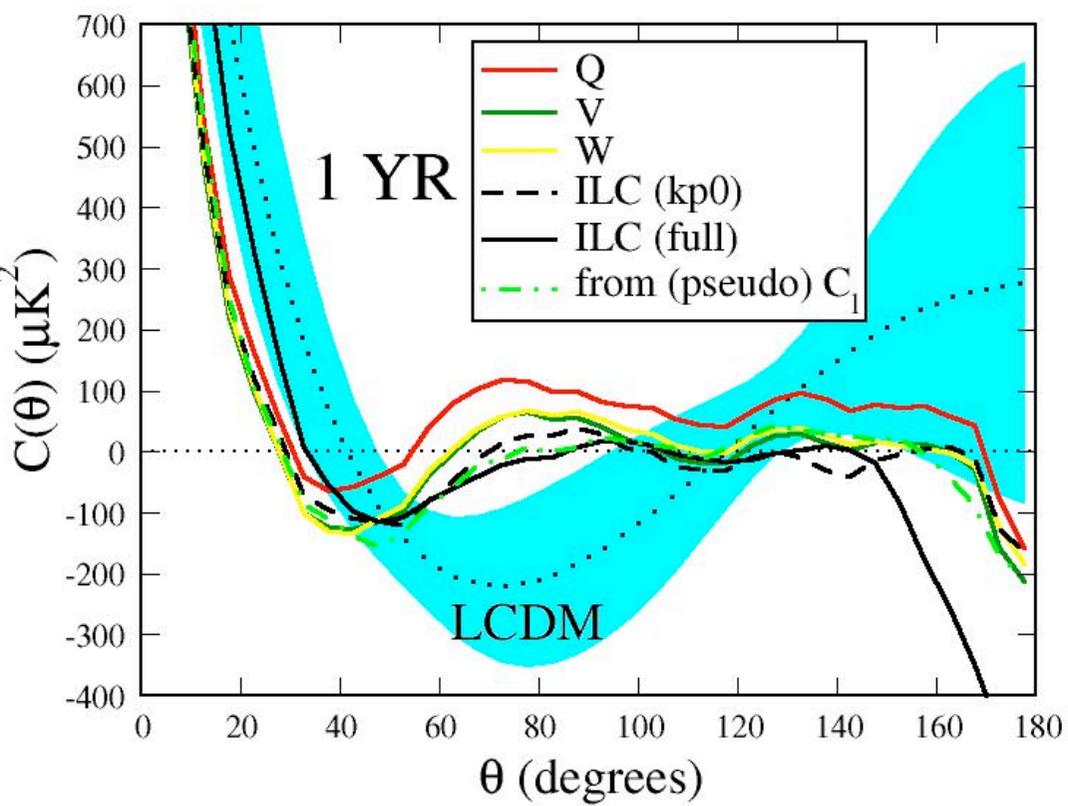


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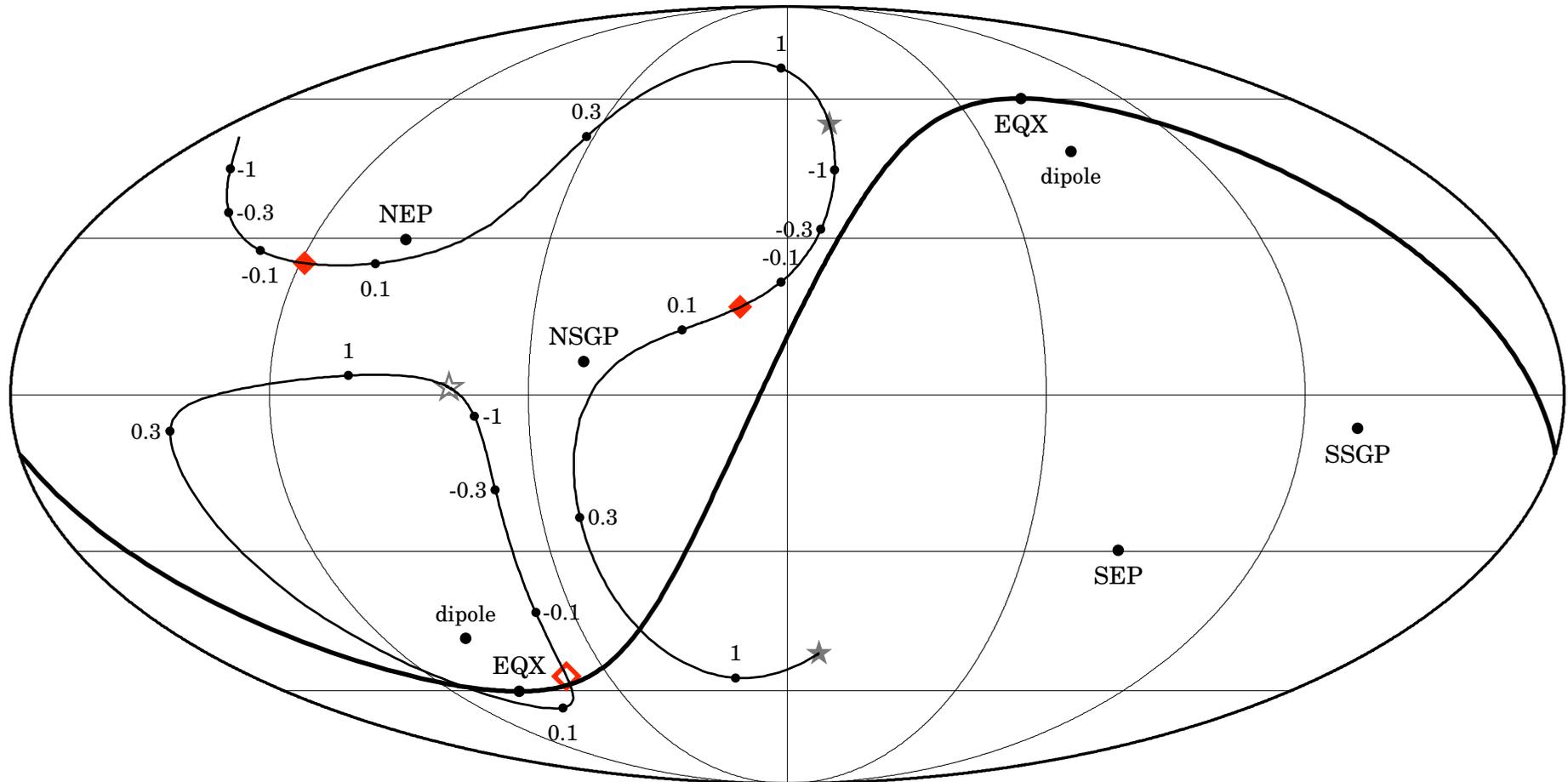
Future data and prospects

- **WMAP** is probably as good as it will get on large scales (as seen in year 1 vs year 123)
- Nevertheless, understanding of **fine details** is improving and is crucial.
- **Planck** will provide a great check of these measurements (very different experiment)
- **Polarization maps** with relatively high S/N, when eventually available, will provide even more leverage.
- The level of expected polarization “alignments” is model dependent
- In principle, can map out largest-scale fluctuations from wide-field, large-volume **large-scale structure surveys** (e.g. LSST; Zhan, Knox et al 2005)

Conclusions

- Alignments with the **ecliptic plane and/or dipole** are sufficiently significant to be very interesting despite the a posteriori nature of these observations
- No convincing explanations so far
- Other observed anomalies (N/S asymmetry, L=4-6 etc) very intriguing and possibly related
- Multipole vectors are a great tool to study alignments and directionalities in the CMB
- **Pixel-space $C(\theta)$ low at 99.97% CL - even more than in year 1; issues still unresolved**

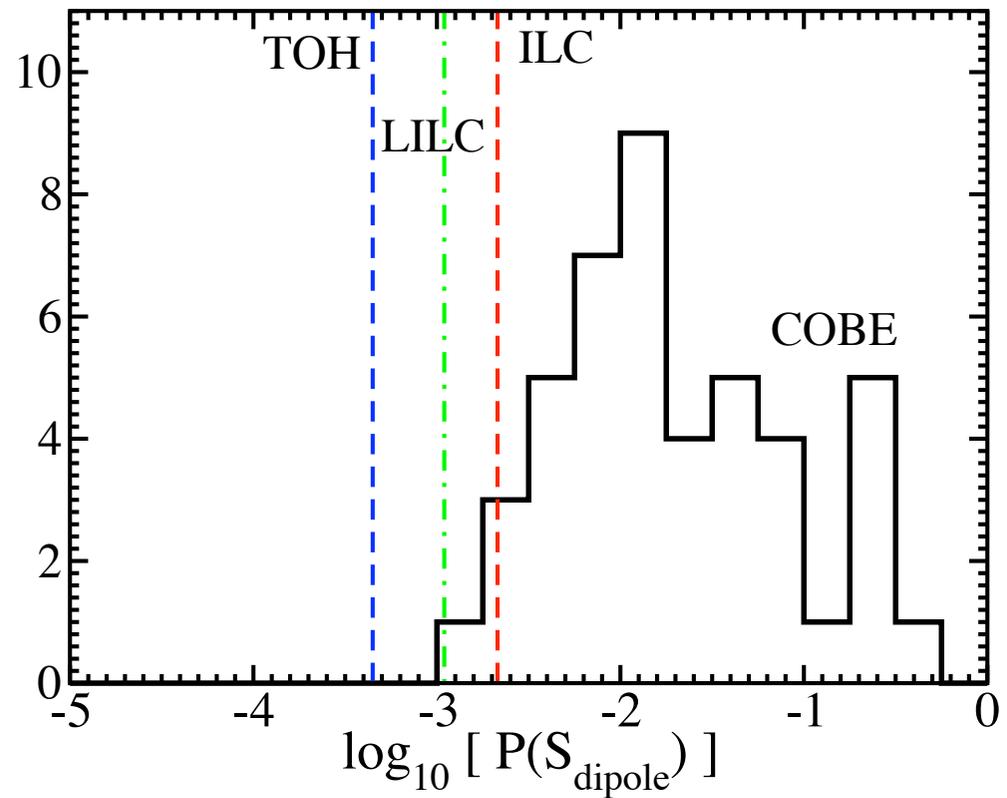
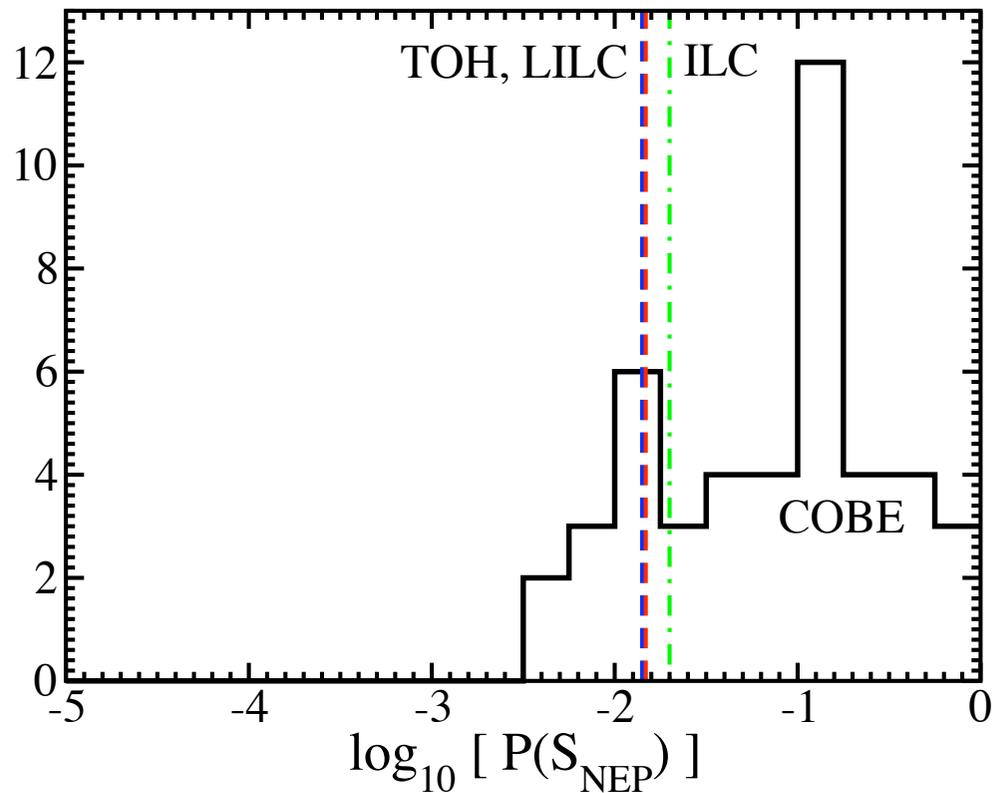
Systematic checks: foreground missubtraction



Adding (known) foregrounds leads to **galactic**,
and not ecliptic, alignments

What about COBE?

Using COBE MCMC maps from Wandelt, Larson & Lakshminarayanan 2003



Example: lensing of the dipole

Small scale anisotropy is induced by the “moving cluster effect” (or, nonlinear ISW effect)

Picks up the **dipole direction** “for free”; itself has a **dipolar pattern** around the center of mass

Sadly, it's way too small:

$$\frac{\Delta T}{T} = 0.5 \mu\text{K} \left(\frac{v_{\perp}}{300 \text{ km sec}^{-1}} \right) \left(\frac{M}{10^{16} M_{\text{sun}}} \right) \left(\frac{R}{10 \text{ Mpc}} \right)^{-1}$$

